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13. ABSTRACT (Maximum 200 words)

The purpose of this project was to advance the understanding of the propagation of ultrafast picosecond electromagnetic pulses in Biological solutions and ultimately, in human tissue. Present day standards of the allowed electromagnetic doses do not include dispersion, modulation or envelope effects, memory or nonlinearity. It is well-known experimentally that biological solutions are highly dispersive. It is plausible, but not established, that modulation, memory and nonlinearity may be important in biological solutions. Hence, this project represents a first step toward better standards.

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REPORT ON AFOSR 89-0311

Microscopic Models for Electromagnetic Wave Propagation in Highly Dispersive Media

PI Professor Brian DeFacio
Department of Physics
University of Missouri
Columbia, MO 65211

April 1989-June 1990

June 18, 1990

1. Discussion

The purpose of this project was to advance the understanding of the propagation of ultrafast picosecond electromagnetic pulses in Biological solutions and ultimately, in human tissue. Present day standards of the allowed electromagnetic doses do not include dispersion, modulation or envelope effects, memory or nonlinearity. It is well-known experimentally that biological solutions are highly dispersive.[7] It is plausible, but not established, that modulation, memory and nonlinearity may be important in biological solutions. Hence, this project represents a first step toward better standards.

The research completed under this grant involved the study of the dispersive dielectric response functions $\in(\omega)$ and $\in(\omega, \vec{k})$ of water, with an emphasis on distilled water in the temperature range $0°C < T < 100°C$. This fluid is 85% of the tissue which the Radiation Analysis Group of the Brooks Air Force Base must understand for decisions involving health and safety. It represents a first step toward understanding pulses in tissue. Some work was also addressed toward understanding pulses in tissue. Some work was also addressed toward understanding the complications which are introduced by membranes. The 10-50Å membrane widths act as sharp interfaces to the microwave carrier with wavelength $\lambda \sim 1$ cm, and some membranes have a strong stern-layer electrostatic potential $\sim 10^8$ V/cm. This work is continuing with the support of a three year DARPA research grant, AFOSR 90.

The purpose of the dielectric response work is to produce better models of the dispersion which are consistent with all available experimental data. Reichl and collaborators[2, 3] have generalized the rotational Brownian motion of McConnell[4] to include memory, as well as inertia effects in $\in(\omega)$. This has been extended using quantum field theoretic; QFT, methods and the Kubo formula to include more general rotations, the effects of pressure and temperature and to show the classes of density fluctuations in $\vec{x}$ which give spatial dispersion, ie, the $\vec{k}$-dependance of $\in(\omega, \vec{k})$. The presence of spatial dispersion requires a more general treatment of the ultrashort pulses, ie whereas $\in(\omega)$ lives on the upper-half complex plane the response $\in(\omega, \vec{k})$ lives on some Riemann surface which is determined by the k-dependance.

2. Talks and Publications

Three talks were presented on this work.

1. A one-hour plenary address was delivered at the 700th Birthday celebration of the University of Montpellier in December 1989 at the international meeting, RCP 264. The manuscript of this talk will be published in 1990 by Springer-Verlag in Volume 2 of their new series on Theoretical Imaging and Inverse Problems with Professor P.C. Sabatier, Editor. The talk gives a review of this project for non-biologists and a copy is included in this report.

2. A thirty minute invited talk entitled Dispersive Wave Propagation in Biological Solutions was presented at the University of Alabama-Birmingham Conference on Differential Equations and Mathematical Physics in March 1990. A Xerox copy of the abstract to this talk is included as part of this report.

3. A poster paper was presented at the NSF-CBMS Conference on Wavelets at Lowell University in MA in June 1990. The title of the paper was, "Wavelets in Inverse Scattering," and the Workshop entitled, "Applications to physics and inverse problems," was chaired by DeFacio. A copy of the Preliminary Program is enclosed with a copy of the posters. One publication on the project entitled"Classical, Linear, Electromagnetic Impedance Theory with Infinite Integrable Discontinuities" has been accepted and is scheduled to appear in the Journal of Mathematical paper which treats electromagnetic scattering from materials bearing infinite, integrable discontinuities as relevant to the membrane problem. Dr. Albanese is (and two of his co-workers) are thanked in the Acknowledgement of this paper for an excellent question. This work is relevant to the formulation of E and M scattering by membranes in a biological solution.

3. Follow-on Studies.

The work to date has shown that the permanent electric dipole moment of water $\vec{p}_w$, can be obtained from an effective potential model using a Lenard-Jones potential in dimensionless radius r,

$$V_{LJ}(r) = V_0\left[\frac{1}{r^{12}} - \frac{1}{r^6}\right]. \tag{1}$$

The dispersive dielectric response

$$\frac{\epsilon(\omega) - \epsilon_\infty}{\epsilon_0 - \epsilon_\infty} = 1 - i\omega \int_0^\infty dt\; e^{i\omega t} \frac{\langle \vec{p}_w(1) \cdot \vec{p}_w(0)\rangle_{EQ}}{\langle p_w^2(0)\rangle_{EQ}} \tag{2}$$

was to be found using QFT to approximate the thermal-equilibrium dipole correlation functions $<\cdot>_{EQ}$ instead of rotational Brownian motion. If these results by the PI hold up using a more realistic Morse potential, $x = \frac{r - r_0}{r}$,

$$V_m(r) = V_0\left[e^{-2\alpha x} - 2e^{-\alpha x}\right], \tag{3}$$

in the MS thesis now underway by Mr. James McClune, at Missouri, they will be submitted for publication at the end of the summer.

Two sources of $\vec{x}$-dependance ($\vec{k}$-dependance in Fourier transform variables) have been identified. One is bubbles or cavitation which scatter the propagating electromagnetic wave. The other is "clusters" or "fluid cells" which serve as time-dependent coherent structures in the fluid.

There is a lot of information in the detailed structure of the formation of Sommerfeld and Brillouin precursors in a dispersive medium. The (small) disagreement between the experiment by Albanese, Penn and Medina[5] and Brillouin's 1914 asymptotic expression shows that the model dielectric response which he used,

$$\epsilon(\omega) = \frac{(\omega - \omega_A)\ (\omega - \omega_B)}{(\omega + \omega_C)\ (\omega + \omega_D)}, \tag{4}$$

is <u>incorrect</u> in biological solutions. (It seems to be experimentally correct in YtFe-Garnet fibers, however.) The idea which is being explored is that a small correction to Eq. (4), above, is needed and that experiment will choose from one of the theoretical calculations. It is emphasized that a model interaction, Eqs. (1) or (3) from molecular physics are used and the correlation function is calculated approximately. Wavelets together with inverse scattering techniques are being used to find the experimental dielectric response. It will be necessary to formulate the memory and non-linearity correctly to extract the information in the pulse propagation in these highly dispersive media. This information will require careful, painstaking study. However, it will make a scientific determination of the effects of microwave on tissue possible, for the first time.

REFERENCES

1. E.H. Grant, R.H. Shepard and G.P. South, *Dielectric Behavior of Molecules in Solution* (Oxford University Press, Oxford, 1978).

2. L.E. Reichl, Phys. Rev. Lett. **49**, 85 (1982).

3. L.C. Sparling, L.E. Reichl and J.E. Sedak, Phys. Rev. **A33**, 699 (1986).

4. J. McConnell, *Rotational Brownian Motion and Dielectric Theory* (Academic Press, New York, NY, 1980)

5. R. Albanese, J. Penn and R. Medina, J. Opt. Soc. Am. **6**, 1441-1446 (1989).

UNIV. ALABAMA - BIRMINGHAM

INTERNATIONAL CONFERENCE ON

DIFFERENTIAL EQUATIONS AND

MATHEMATICAL PHYSICS

May 15-22, 1990

Dispersive Wave Propagation in Biological Solutions*

B. DEFACIO

Biological solutions are experimentally known to be highly dispersive media for electromagnetic wave propagation. Some work on the dielectric response of these solutions which includes inertia and memory effects will be presented.

The time-domain electromagnetic wave propagation in these media will be discussed with particular attention paid to dispersion effects. A wavelet approach in a special time-frequency phase space is given next. The phase space is cut-off on the time side to accommodate physical causality. Some implications for inverse scattering theory are mentioned.

* Work supported in part by AFOSR Grant 89-0311.

Department of Physics & Astronomy. Missouri University. Columbia. MO 65211

Lowell, MASS June 1990

NSF/CBMS Conference on Wavelets: Preliminary Program

Mon. June 11:			
8:30- 9:15	Registration		
9:20- 9:30	Preliminaries		
9:30-10:30	I. Daubechies	AT&T Bell Labs	Principal Lecturer
11:00-11:50	A.Willsky	MIT	*Modeling and estimation for multiresolution stochastic processes*
1:30- 2:30	I. Daubechies		
2:30- 3:20	K. Grochenig	Univ. of Connecticut	*Nonorthognal wavelets, Gabor expansions and group representations*
3:50- 4:40	G. Battle	Texas A&M	*Block spin construction of ondelettes & quantum field theory*
Tues. June 12:			
9:20-10:10	C. Chui	Texas A&M	*A cardinal spline approach to wavelets*
10:45-11:45	I. Daubechies		
1:30- 2:30	I. Daubechies		
2:30- 5:00	Posters		
3:30- 5:00	Workshops	B. DeFacio, *Application to physics and inverse problems* H. Feichtinger, *Group theory and harmonic analysis* M. Vetterli, *Signal analysis*	
Wed. June 13:			
8:45- 9:45	B. Torresani	Marseille	*Wavelet analysis of asymptotic signals*
9:50-10:30	S. Mallat	Courant	*A characterization of signals with the wavelet transform maxima*
11:00-12:00	I. Daubechies		
1:15- 2:15	I. Daubechies		
Thur. June 14:			
9:20-10:10	G. Beylkin	Schlumberger-Doll	*Fast numerical algorithms and wavelets I*
10:45-11:45	I. Daubechies		
1:30- 2:30	I. Daubechies		
2:30- 3:20	R. Coifman	Yale	*Fast numerical algorithms and wavelets II*
3:50- 4:40	J. Liandrat	Marseille	*Numerical resolution of non-linear diff. equations: Burger's equation*
Fri. June 15:			
9:20-10:10	A. Cohen	Paris	*Wavelets and digital signal processing*
10:45-11:45	I. Daubechies		
1:15- 2:15	I. Daubechies		

Registration and coffee breaks will be on the second floor of the Olsen (math) building.
Lectures will be in Ball 214, directly across the street from Olsen.

Lunch will be served in Olney 428.
Posters and workshops will be on the third floor of Olsen.

WAVELETS IN INVERSE SCATTERING*

B. De Facio, MU Physics
&
Grant V. Welland, UMSL Math

⟹ *AFOSR 89-0311 & AFOSR 90-

$u(\cdot,\cdot) \in S'(\mathbb{R}^3 \times T)$

$$\Delta u - u_{tt} = V(\vec{x})\, u(\vec{x},t)$$

$t \to -\infty$.

$$u \sim u_0(\vec{x}, -\infty)$$

$t \to +\infty$.

$$u \sim u_0 + \frac{R\left(t - t' - \frac{|\vec{x}-\vec{x}'|}{c}, e', e\right)}{r}$$

$R = L_{chan}\{r\,(u-u_0)\}$

Direct scattering problems

Given $V(\vec{x})$ find $R(\cdot,\cdot,\cdot)$, if any exists. If $\exists V$ uniqueness? construction? stability

Inverse scattering problems

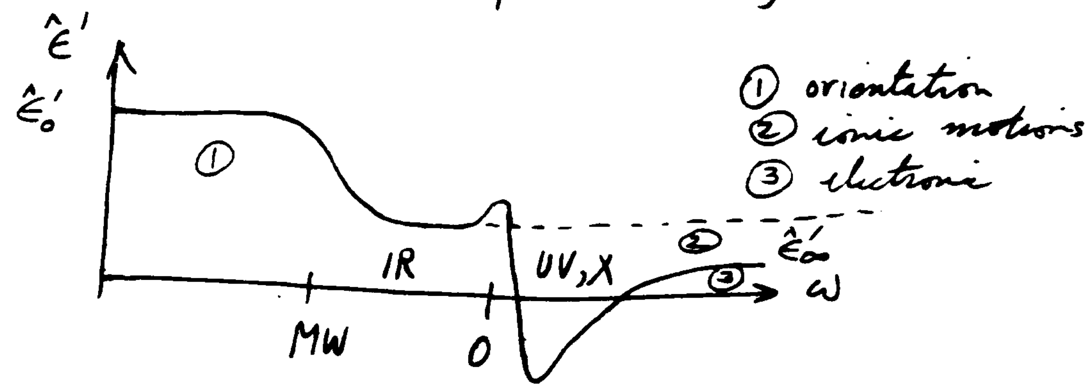
Given enough R's find V. Does $R \Rightarrow V$? ∂_k.

Filters, sliding FT windows. usual, (*)

$$u \rightarrow \begin{pmatrix} \vec{E} \\ \vec{H} \end{pmatrix}, \quad V \rightarrow \epsilon(\vec{x},t),\ \mu(\vec{x},t),\ \sigma(\vec{x},t)$$

Biomathematical model for ϵ

$$\left.\begin{aligned} \hat{\epsilon}(\omega) &= \hat{\epsilon}' + i\,\hat{\epsilon}'' \\ \epsilon'' &= H_T(\epsilon') \end{aligned}\right\}$$ Dielectric response Grant, et al



Tissue

85% H_2O
14.9% Nucleic acids, protiens, lipids, DNA
.1% Trace elements.

Strong ω dependance of $\hat{\epsilon}$ called dispersion of ϵ, $\omega \neq ck$ dispersion of ω

Debye, Langevin $\displaystyle\int_0^\infty e^{-i\alpha t}\,dt = \frac{1}{-i\alpha} = \frac{i}{(\alpha_1 + i\alpha_2)}$

$$\int_{4\pi} \rightarrow \frac{1}{3}$$

Family $\psi_{a,b}(t)$ generated from ψ by dilations and translations

$$\psi_{a,b}(t) = \psi\left(\frac{t-b}{a}\right)$$

a = dilation parameter, scale
b = x-lation parameter

large $a \Rightarrow \psi_{a,b}$ large supp $\Rightarrow$ low freq.

t one-variable description

a, b = 2-variable phase space description

D. $$C_{a,b}(\psi) := \int_{-\infty}^{\infty} s(t)\, \psi_{a,b}(t)\, dt = \begin{cases} \text{wavelet coeff} \\ \text{of signal } s(t) \end{cases}$$

= Direct signal analysis

1) <u>Compression</u>: $C_{a,b}(\psi)$'s depend on the "local freq" in a certain time interval

Also, edge detection. Observe, no aliasing

I. $$s(t) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} C_{a,b}(\psi)\, \psi_{a,b}(t)\, da\, db$$

= inverse signal analysis

1) <u>Something new:</u>

Albanese et al measure $B(\omega)$ to better than 1% accuracy and find 3-4% difference in theory : exp. ∴ model inadequate, somehow.

a) bubbles, density fluctuations $\Longrightarrow$

$$\hat{\epsilon} = \hat{\epsilon}(\omega, \vec{k})$$

$\vec{k}$ dependence $\Rightarrow$ Rieman sheets & correction terms due to new branch cuts.

b) B. Jawerth, G. V. Welland, + indep. S. Mallet zero crossings using wavelets.
non-⊥ or multi-mother wavelets.

$$B(\omega) = f_B(\omega)\, A_i(\omega)$$

measured $u(\omega) \neq B(\omega)$!

Seek $B_{exp}(\omega)$ using inverse scattering and J-W zero crossing. This gives the dispersion of the medium! ⇗ Borg